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High-frequency dynamic response of thin plate with uncertain parameter based on average wavelet finite element method (AWFEM)

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ABSTRACT

Due to the limitation caused by the low computational efficiency and parameters uncertainty, the Traditional Finite Element Methods (TFEMs) based on the general polynomials cannot provide reliable numerical solutions in the high-frequency domain. To this end, the Average Wavelet Finite Element Method (AWFEM) is proposed in this paper for dealing with the low computational efficiency and uncertain parameters at one time. Thus, the essential formulas of the AWFEM are derived based on the Wavelet Finite Element Methods (WFEMs) and average statistic algorithm. Besides, to divide the wide-frequency domain into the low and high-frequency domain, the Frequency Domain Index (FDI) is constructed based on the resonant mode number in bandwidth. Later, to investigate the proposed method's prediction ability in the high-frequency domain, the dynamic response of the numerical models under various classical boundary conditions and non-uniform mass distributions are computed by AWFEM and Statistical Energy Analysis (SEA), respectively. And, the numerical results show that the AWFEM can be applied for predicting dynamic response in the high-frequency domain as same as SEA. Besides, the CPU time is less than 5 min to capture the numerical solutions based on personal computer. Most notably, it gives us an optional choice to predict dynamic response in the high-frequency domain only based on finite element models.

1. Introduction

Nowadays, with the significant development of civil and defense equipment, some of them will subject to the extremely aerodynamic heat and the high-frequency exciting under operation conditions [1]. Thus, to perform better predesign about the sound and vibration performance, it is necessary to predict dynamic response of these equipment in the high-frequency domain accurately, especially for some advanced equipment, such as submarine, airfoil, etc. Currently, the numerical methods to proceed dynamic analysis can be divided into two categories in the field of sound and vibration analysis [2,3]. One is the Statistical Energy Analysis (SEA) mainly based on the theory of statistics and energy. The other is the Traditional Finite Element Methods (TFEMs) mostly based on the general polynomials.

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(1) In the field of sound and vibration analysis, the SEA has been widely applied for proceeding dynamic analysis in the high-frequency domain, and many advanced methods had been proposed based on the SEA and are suitable for many other high-frequency dynamic response prediction problem [4–14]. Moreover, the corresponding numerical solutions can be widely accepted for improving the products' sound and vibration performance in the high-frequency domain. But, due to the theoretical assumptions, such as a sufficient number of resonant modes, weak coupling, the application of SEA is practically limited in the high-frequency domain [15]. Besides, some essential parameters, such as loss factors, are always computed by the finite element methods in practice.
(2) As well known, due to the much better universality, TFEMs have been widely applied for performing dynamic analysis in engineering. However, due to the low computing efficiency and uncertain parameters, the application of TFEMs is limited in the low-frequency domain and cannot provide reliable numerical solutions in the high-frequency domain [16–18]. Nevertheless, its great universality still has attracted much attention in the field of sound and vibration analysis.

Obviously, by analyzing these two kinds of numerical methods, we can easily find that the SEA is the only way to proceed dynamic analysis in the high-frequency domain in practice. However, its application still is limited in practice. It is mainly due to that the SEA cannot be widely accepted and used by engineers, because of its universality being much worse than finite element methods. Besides, as mention above, it is necessary to construct the finite element models and predict some parameters which are very relevant to SEA. In other words, the engineers must build the SEA model and finite element model at one time. Thus, we can easily conclude that the SEA cannot be widely used by engineers, and most of the engineers are used to applying finite element methods for performing dynamic analysis in engineering.

Thus, to predict the high-frequency dynamic response efficiently, it is necessary to propose one finite element method, which is efficient in the high-frequency domain. For this purpose, this paper focus on introducing one finite element method to break up the limitation caused by the low computing efficiency and uncertain parameters in the high-frequency domain. To facilitate the readers to understand the limitation, the low computing efficiency and uncertain parameters of TFEMs will be introduced detailedly in follows.

Due to the low computational efficiency, the number of elements to model per wavelength is greater than 6 at least when proceeding dynamic analysis based on TFEMs. And, the wavelength will decrease rapidly as the growth of frequency. Thus, the corresponding computational cost will be enormous in the high-frequency domain. For example, the number of Degree of Freedoms (DOFs) applied for predicting the dynamic response of a 2 m length of aircraft fuselage within 225 Hz will reach 550,000 [17]. Based on this, we can easily deduce that the computational cost will be enormous and cannot be accepted by engineers anymore when modeling the aircraft fuselage under operating conditions in engineering, because then the force excitation frequency may reach 3000 Hz. Even under the current high computational power, the computational cost and CPU time still cannot be accepted by engineers in the high-frequency domain. Thus, it is necessary to overcome the low computational efficiency when proceeding dynamic analysis in the high-frequency domain based on finite element methods.

Besides, due to the uncertain parameters, the dynamic response predicted by TFEMs will be distortion in the high-frequency domain [19]. It is a significant problem, even if the computational power of the advanced computers will be significantly developed in the future, and the computational process can be reduced to a reasonable amount of CPU time in the high-frequency domain. It is mainly due to that the uncertain parameters will finally cause the numerical solutions to be unavailable in the high-frequency domain. Obviously, to predict dynamic response in the high-frequency domain based on finite element methods, the only way is to construct the accurate numerical models and avoid the uncertain parameters. Obviously, it is hardly possible to build the accurate numerical models without any uncertain parameters. Thus, the uncertain parameters will always exist in the process of proceeding numerical analysis. In this study, the uncertain parameters indicate that the properties of the structures are uncertain, such as uncertain boundary conditions, uncertain mass distribution, etc. In conclusion, we can easily find that it is essential to consider the influence of the uncertain parameters when predicting dynamic response in the high-frequency domain based on finite element methods.

Based on above discussion, due to the limitation caused by the low computing efficiency and uncertain parameters, the TFEMs are practically limited in the low-frequency domain. Thus, to break up the limitation and to provide reliable numerical solutions in the high-frequency domain, it is necessary to deal with these two kinds of problems of TFEMs at one time. For this purpose, this paper will introduce the Wavelet Finite Element Methods (WFEMs) into this article. To facilitate the readers to understand the WFEMs and its characteristics, the research status of WFEMs will be introduced briefly in follows.

In 1995, Ko et al. [20] firstly applied the Daubechies wavelet for constructing wavelet element and performing the simple numerical analysis. Later, Chen et al. [21] applied the two-dimensional Daubechies wavelet for constructing the wavelet element and analyzing the plate-bending problem. And, to obtain desirable computing accuracy, the B-spline wavelet functions have been applied for constructing the efficient elements and performing structures analysis [22–24]. Recently, according to the Refs. [25–35], the WFEMs have been improved to perform more complex numerical analysis for various kinds of structures, such as the thin plate, skew plate, composite structures, etc. Most notably, these methods own much better computing efficiency compared with TFEMs. In 2017, Geng et al. [18] have successfully applied the WFEMs for predicting the dynamic information in the high-frequency domain without considering the uncertain parameters. Thus, we can easily conclude that the limitation caused by the low computing efficiency of TFEMs can be broken up by WFEMs. However, like the TFEMs, the uncertain parameters will lead to the unavailable numerical solutions when applied the existing WFEMs for performing